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Associations between Atlantic cod (*Gadus morhua*) and hydrographic variables: implications for the management of the 4VsW cod stock

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Many groundfish stocks on the Atlantic coast of North America are monitored by bottom trawl surveys which use a stratified random design. The resulting estimates of abundance often exhibit high variability within and between surveys, particularly on inter-annual time scales, and inconsistencies in the estimates of relative year-class strength over time. These inconsistencies, or *year-effects*, may reflect changes in the distribution or catchability of the fish that may be related in turn to environmental factors such as water temperature and salinity. The estimates of cod abundance derived from the research vessel trawl surveys conducted in July over the eastern Scotian Shelf in NAFO areas 4Vs and 4W from 1970–1993 are shown to exhibit these features. Analyses of these survey data also show that cod exhibit age- and area-specific associations with near-bottom water temperature and salinity ranges that are consistent with the properties of a Cold Intermediate Layer (CIL) water mass in the area and that inter-annual variability in the estimates of abundance is correlated with the area of the bottom found within the CIL. A model relating the variability in the CIL to the estimates of age-specific cod abundance obtained from the surveys was used to derive new survey indices of abundance. These new indices do not have detectable *year-effects* and may provide more consistent estimates of true relative year-class strength than the original time series.

Key words: abundance indices, cold intermediate layer water mass, stratified random design, stock assessment, trawl surveys, year-effects.

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Introduction

Annual or more frequent bottom trawl surveys provide the major source of fisheries-independent information on abundance, species composition, and basic biological data for the groundfish communities of the Atlantic Coast of Canada and the United States (e.g. Azarovitz, 1981; Halliday and Koeller, 1981; Pitt *et al.*, 1981; Mahon *et al.*, 1984; Strong and Hanke, 1995). Most of these surveys use a stratified random design with strata boundaries defined by depth ranges, species-specific distributions, and management areas. The abundance estimates of fish from these surveys are routinely used in the stock assessments of most commercial groundfish species (Gunderson, 1993).

In general, abundance indices from trawl surveys are highly variable both for within year estimates and for estimates of trends in abundance over time. Indeed, annual abundance estimates often change more rapidly between adjacent years than the population dynamics of the species would be expected to allow (Smith, 1988a). These sudden changes are often referred to as *year-effects* by stock assessment scientists.

Research on methods of improving the precision of within-year estimates of abundance from trawl surveys has mainly concentrated on either modifying the estimates (e.g. Pennington, 1986; Smith, 1988b; McConnaughey and Conquest, 1993) or modifying aspects of the survey design (e.g. Francis, 1984; Heisey and Hoenig, 1986; Gavaris and Smith, 1987; Jolly and

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Hampton, 1990; Smith and Gavaris, 1993). Smith (1990) discussed the application of statistical models and their specific estimators to survey data, and showed that biased estimates can easily result from such an approach (see also Jolly and Hampton, 1990; Myers and Pepin, 1990).

While some of the above techniques have been successful in providing more precise estimates of abundance within a year, they are not useful for explaining the large inter-annual changes observed in trawl survey abundance indices. Pennington (1986) combined the Δ-distribution approach for within-year variability with an autoregressive integrated moving average time-series model for the trend in the mean abundance over time. Pennington assumed that deviations of the observed trend from the predicted trend reflected unexplained changes in the catchability of the target fish species by the survey gear.

Recent studies have shown that a number of groundfish species exhibit strong and repeatable associations for a particular range of depths, temperatures, or salinities, or some combination thereof (Scott, 1982; Smith *et al.*, 1991; Sinclair, 1992; D'Amours, 1993; Page *et al.*, 1994; Perry and Smith, 1994; Smith *et al.*, 1994; Swain and Kramer, 1995). There is also ample evidence that the amount of bottom water that exhibits these seemingly preferred characteristics or the amount of bottom water of this type being sampled can fluctuate over time and may therefore affect the availability or catchability of the species being surveyed by the trawl (Smith *et al.*, 1991; Page *et al.*, 1994; Smith and Page, 1994; Smith *et al.*, 1994). Unsuitable conditions in the water near the bottom may keep fish off-bottom and unavailable to the trawl. While time-series methods such as those considered by Pennington (1986) may be useful for modelling trends in abundance from trawl surveys, studies of the environmental associations of species can give us an insight into why seemingly abrupt changes in abundance can occur. Understanding the underlying biological mechanisms will lead to greater confidence in interpreting abundance trends.

Smith *et al.* (1991) studied these sudden changes in age 4 cod (*Gadus morhua*) survey indices from the March surveys in NAFO (Northwest Atlantic Fisheries Organization) area 4VsW over the period 1979–1988. They concluded that the cod caught in the bottom trawl were most associated with water exhibiting the characteristics of the Cold Intermediate Layer (CIL): water mass salinity between 32 and 33.5 psu (practical salinity units, Fofonoff, 1985) and temperatures less than 5°C (as defined by Hachey, 1942). Sudden changes or *year-effects* were often found to be associated with increases in the amount of CIL water encountered by the trawl.

In this paper we analyze the abundance indices for cod of ages 1 to 8 from the July surveys of 4VsW over the period 1970–1993. Recent findings and new statistical methods (e.g. Perry and Smith, 1994) allow us to show that cod exhibited associations with the CIL in the summer survey but that the strength of these associations were age and area specific. Considering that annual fluctuations in the amount of CIL impinging on the bottom may affect the availability of the cod to the trawl, we developed a statistical model of cod abundance which was a function of the annual patterns in the CIL. The residuals from this model were compared with the original stratified mean series and shown to no longer exhibit *year-effects*.

Materials and methods

The fish catch and hydrographic data sets presented here were obtained from the standard groundfish bottom trawl surveys of the Scotian Shelf conducted by the Marine Fish Division (Bedford Institute of Oceanography, Dartmouth, N.S.) and Biological Station (St Andrews, N.B.) of the Canadian Department of Fisheries and Oceans. These surveys have been conducted every summer on the Scotian Shelf since 1970. The surveys used a stratified random survey design (Cochran, 1977). The Scotian Shelf strata (Fig. 1) are primarily based on depth ranges of 0–91 m, 92–183 m, and 184–366 m (originally 0–50 fm, 51–100 fm, and 100–200 fm). Further delineations of the strata boundaries reflect species/stock distributions and other considerations (Doubleday, 1981; Halliday and Koeller, 1981).

The sample unit for the survey was defined as the area over the bottom covered by a trawl 12.5 m wide towed at 3.5 knots for a distance of 1.75 nautical miles. These sample units or sets were selected before the cruise and randomly located in each stratum.

The near-bottom hydrographic data were collected immediately following each tow of the trawl over the bottom. Samples were taken by vertical casts of water sample bottles and after 1989 by a Sea-Bird model 19 (Sea Bird Electronics, WA, USA) or 25 CTD (Conductivity, Temperature and Depth) profiler. Note that sampling the hydrography in this way cannot resolve variability and fish–environment associations of scales finer than the length of a tow.

Abundance indices were calculated using standard formulations for stratified random designs. Smith (1988a) discusses these aspects in detail as they apply to the groundfish surveys. The indices for a particular species were constructed using results only from those strata which cover a particular fisheries management area. For example, the eastern Scotian Shelf cod stock was designated as occurring in NAFO management areas 4Vs and 4W, respectively strata 43–52 and 53–66 (see Fig. 1).

Comparisons between the distribution of fish and concurrent environmental conditions, such as temperature, salinity, and depth, were made using the catch-weighted

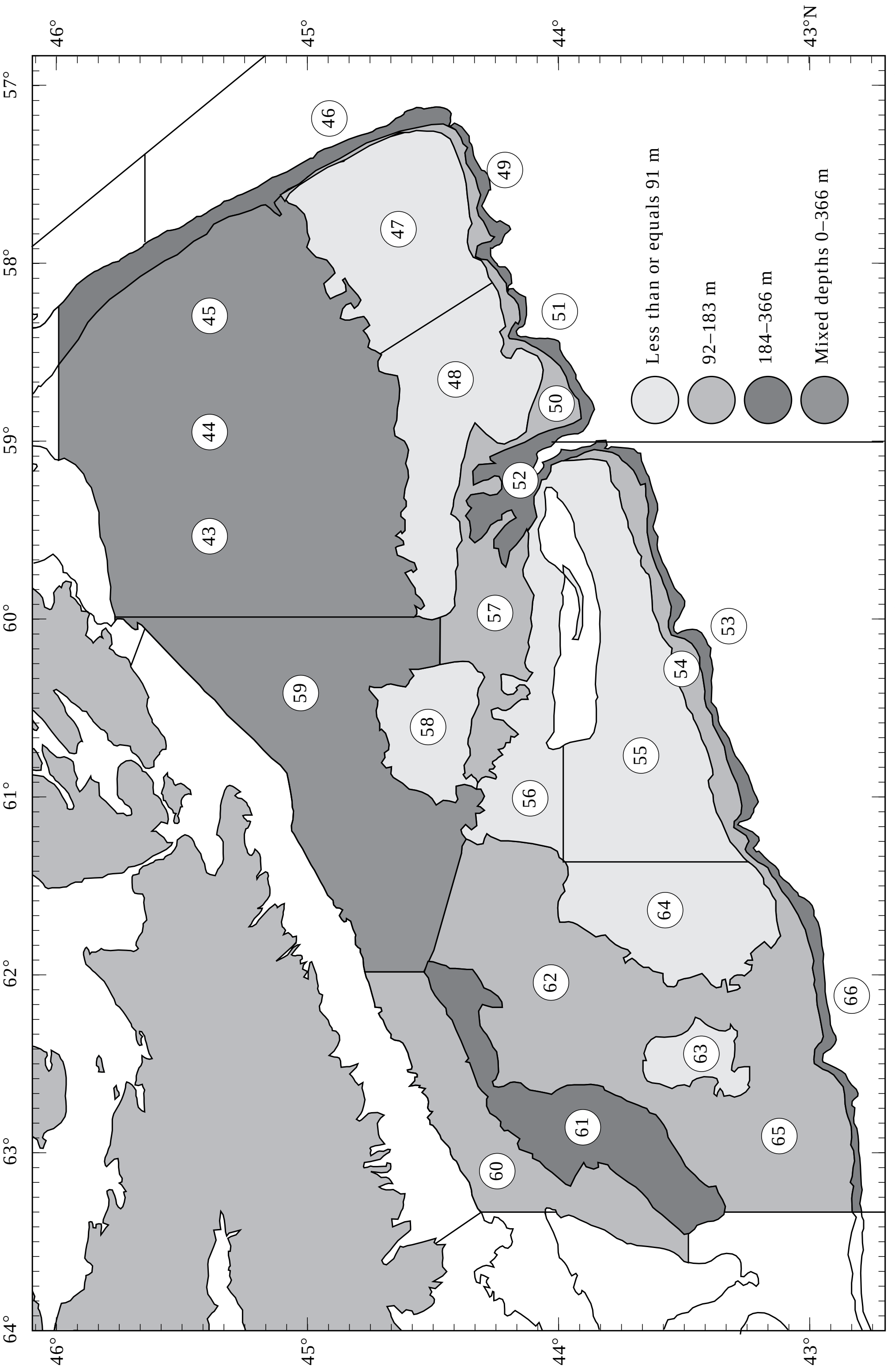


Figure 1. Stratification map for the Scotian Shelf surveys in NAFO area 4VsW. Stratum boundaries are based primarily on depth ranges (originally measured in fathoms). The numbers on the map identify the individual strata.

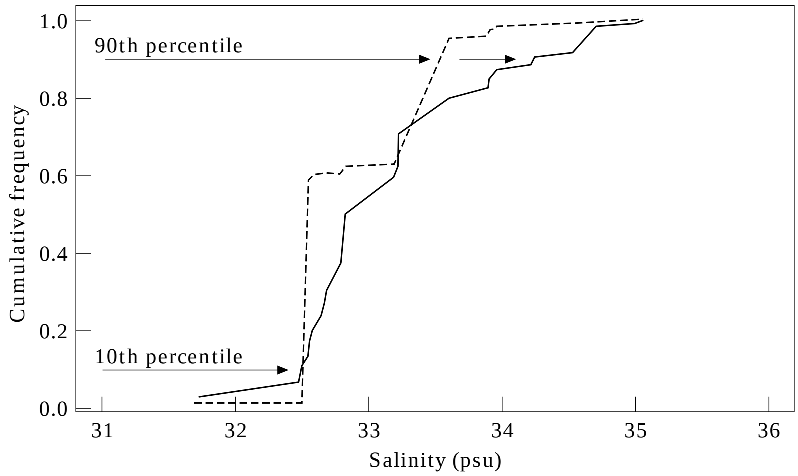


Figure 2. Cumulative frequency distributions of salinity and catch-weighted salinity for age 5 cod in NAFO management areas 4Vs of the Eastern Scotian Shelf, Canada (1984 survey). (——) Salinity; (– – –) catch-weighted.

cumulative distribution function approach developed by Perry and Smith (1994) and used recently for all of the Canadian surveys of all of the cod stocks (all ages) on the Scotian Shelf and Georges Bank by Page *et al.* (1994). In this method the general frequency distribution of the hydrographic variable (depth, temperature, or salinity) was characterized by constructing its empirical cumulative distribution frequency (cdf) curve.

$$f(t_j) = \sum_h \sum_i \frac{W_h}{n_h} I(x_{hij}) \quad (1)$$

where:

$$I(x_{hij}) = \begin{cases} 1, & \text{if } x_{hij} \leq t_j; \\ 0, & \text{otherwise.} \end{cases}$$

and

n_h = the number of hauls or sets in stratum h ($h=1, \ldots, L$),
N_h = the total number of possible sets in stratum h,
$N = \Sigma_{h=1}^{L} N_h$,
$W_h = N_h/N$,
x_{hij} = the measurement for hydrographic variable j in set i of stratum h.
t_j = the ordered observations from lowest to highest of hydrographic variable j.

Commonly, the probability associated with each observation in a cdf is $1/n$ ($n=\Sigma_{h=1}^{L} n_h$); however, the stratified random design results in a probability of $1/n_h$ within each strata. Therefore, the cdf was constructed to incorporate the survey design (Perry and Smith, 1994).

The association between the fish at age a and each hydrographic variable was characterized by a catch-weighted cumulative distribution curve given by

$$g_a(t) = \sum_h \sum_i \frac{W_h}{n_h} \frac{y_{hia}}{\bar{y}_{st,a}} I(x_{hij}) \quad (2)$$

where:

y_{hia} = the number of fish of a specific species of age a caught in set i and stratum h,
$\bar{y}_{ha}$ = the estimated mean abundance of a specific species of fish of age a in stratum h,
$\bar{y}_{st,a} = \Sigma_{h=1}^{L} W_h \bar{y}_{ha}$, the estimated stratified mean abundance for a specific species of fish at age a.

In this approach, catches larger than the stratified mean, $\bar{y}_{st,a}$, would indicate hydrographic conditions with a stronger association for the cod of age group a than conditions where the catches were smaller than the stratified mean.

As an example of this methodology catch-weighted (Equation 2) and available salinities (Equation 1) for age 5 cod in the 1984 survey for 4Vs are plotted in Figure 2. The 10th and 90th percentiles for the salinity cdf were 32.5 and 34.2 psu, respectively, while the corresponding catch-weighted salinity percentiles were 32.5 and 33.5 psu. In general, the cod were caught in a narrower range of salinities than that generally present.

Results

Abundance indices and year effects

The trawl survey time series for the stratified mean number of cod caught per tow in the 4Vs (strata 43–52) and 4W (strata 53–66) management areas are shown in Figure 3. In this figure all age groups were combined into one estimate of abundance per year for each area. The main features of the trends in the two areas are the relative and sudden peaks in the indices in the early

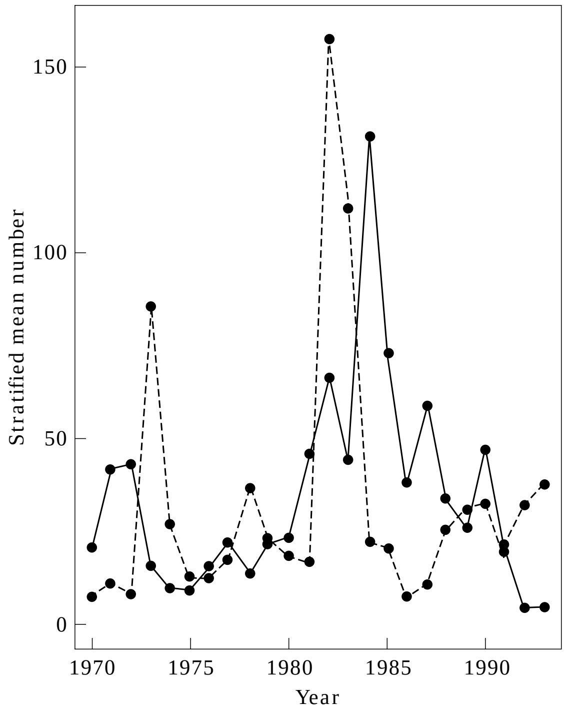


Figure 3. Trends in stratified mean number of cod (*Gadus morhua*) for NAFO management area 4Vs (strata 43–52) and 4W (strata 53–66) from July trawl surveys of the Eastern Scotian Shelf, Canada. (——) 4Vs; (– – –) 4W.

1970s and again in the early 1980s. The difference in phase between the larger peaks in the two areas may be due to the very different age structures in the two areas. While the proportions of 1–3 year-old cod in the survey were large relative to the proportions of older cod and generally similar in 4Vs and 4W during the 1970s, the pattern changed thereafter (Fig. 4). With the exception of 1982 and 1990, age 4 and older cod were the most abundant age groups in the 4Vs index after 1979. Relative to 4Vs the 4W index continued to be dominated by 1–3 year-old cod.

While each area may have its own characteristic age structure and temporal trend, the peaks in both areas have one thing in common, i.e. these peaks often indicate increased abundance for more than just one or two dominant cohorts. In fact, it appears that these survey estimates show increased abundance for most cohorts in one year compared to the estimates from the previous year (see also Smith *et al.*, 1991). The result of these *year-effects* is that our estimate of the relative strength of a cohort can change from year to year. We tested for the existence of such of an effect by using a Friedman rank sum test (Conover, 1980) with ages as blocks and cohorts as treatments. Our null hypothesis was that the relative rankings of the cohorts will be the same over all ages for a specified set of cohorts followed over a series of ages. Application of this test to the stratified means from the 1969 to 1985 cohorts for ages 1–8 resulted in the null hypothesis being rejected for both 4Vs and 4W ($p<0.001$).

This lack of consistency in the estimated relative strengths of cohorts complicates interpretation when these data are used in fisheries population models which try to describe the decline of year-classes as negative exponential functions of fishing and natural mortality. Smith *et al.* (1991) suggested that the *year-effect* reflected more an increase in availability of cod to the survey gear due to changes in environmental conditions than a real increase in abundance.

Environmental relationships

Previous work by ourselves and others on the environmental relationships of cod during trawl surveys has shown that there is strong evidence for age-specific associations with certain salinity (Smith *et al.*, 1991; Page *et al.*, 1994; Perry and Smith, 1994) and temperature ranges (Sinclair, 1992; Page *et al.*, 1994; Swain and Kramer, 1995). Smith *et al.* (1991) showed that, during March bottom-trawl surveys of 4VsW, age 4 cod (only age studied) were mainly associated with bottom water where both the salinities and temperatures were consistent with those of the cold intermediate layer (CIL) water mass.

A summary of the cdf salinity analyses by Page *et al.* (1994) is shown in Figures 5 and 6. These figures compare the available salinities and catch-weighted salinities for cod ages 1 to 8 from the July surveys (1970–1993) in area 4Vs (Fig. 5) and 4W (Fig. 6). On each figure panel the 10th, 50th, and 90th percentiles for each pair of cdf curves for each year are plotted.

The main features of these plots are that the cod were not randomly associating with the available salinities – the distribution of points is not centered along the 1:1 line. In both 4Vs and 4W, the 90th percentiles for all ages fall below the 1:1 line, indicating that the majority of cod avoided the highest salinities available. The catch-weighed 90th percentile points are distributed around 33.5 psu indicating that this is the upper limit of the cod distribution. At the other extreme, the 10th percentiles fall above, below, or around the 1:1 line depending upon age and area. In 4Vs, the distribution of the catch-weighed 10th percentiles for the younger cod is around 32 psu, suggesting this is the lower limit with which these fish associated. The lower limit for the older cod is about 32.5 psu. While in 4W the available salinity range extends to higher salinities, the catch-weighted salinities remain similar to those in 4Vs. Therefore, in both 4Vs and 4W the majority of the cod are found in waters with salinities between 32 and 33.5 psu – the salinities characteristic of the cold intermediate layer (CIL).

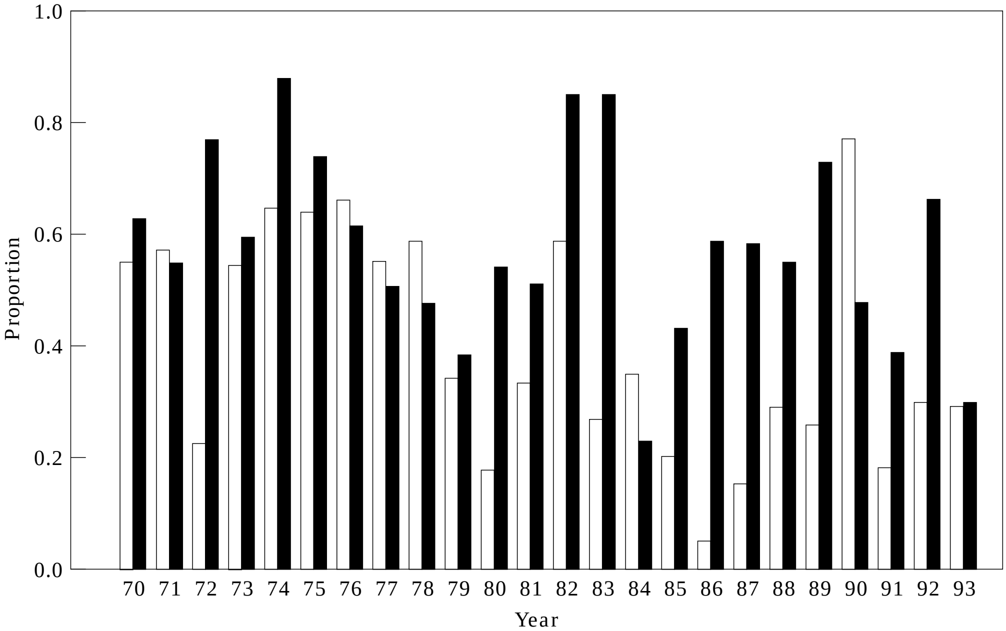


Figure 4. Proportion of stratified mean number per tow of all ages of cod comprised of age one to three year old cod for NAFO management areas 4Vs and 4W of the Eastern Scotian Shelf, Canada. ■ = 4W; □ = 4Vs.

The temperatures associated with the CIL salinity range in the summer survey were amongst the coldest temperatures available in both 4Vs and 4W (Fig. 7). When defined by salinity range alone, this water mass was generally warmer in 4W than it was in 4Vs. This was true even when the upper boundary of <5°C was used to define the water mass, with the long-term average temperature (1970–1993) of the CIL being 2.2°C in 4Vs and 3.1°C in 4W. Note that using the salinity range alone for identifying the CIL will also mainly identify water with the appropriate temperatures for this water mass in 4Vs and 4W.

Having established that cod are mainly associated with the CIL, which has some of the lowest water temperatures within the region, we next quantified the proportion of the survey abundance estimate for cod that comes from waters having the characteristics of the CIL. We looked at this in the following manner. First consider the term $W_h y_{hia}/(n_h \bar{y}_{st,a})$ in Equation (2). This term expresses the proportion of the stratified mean associated with environmental variable x_{hi}. For example, in Figure 2, the salinity range of 32–33.5 psu corresponds to the 1.4th and 88th percentiles of the catch-weighted curve. Therefore, 0.866 of the stratified mean for age 5 cod in 4Vs in 1984 came from water with this salinity range. The proportion of the stratified mean for each age in 4Vs associated with the CIL temperature and salinity ranges for a variety of depth ranges is presented in Figure 8. Each boxplot for the 0–360 m depth range (maximum depth of survey) consists of all 24 years (1970–1993) of data. Looking at the boxplots for this depth range first, we see that there is an increasing tendency with age for greater proportions of the stratified mean to be associated with the CIL salinity and temperature range. In addition, the main signal with respect to fish catch and CIL occurs at depths of roughly 0–150 m. The upper right panel of Figure 8 identifies what proportion of bottom water was CIL. This panel shows that this water mass was mainly confined to the same depth range of 0–150 m with, on average, half of the CIL above or below 100 m.

The results for 4W (Fig. 9) were more variable, although the tendency for greater proportions of the stratified mean to be associated with the CIL with age was still evident. The depth range of 0–150 m also continued to be a good cut-off for the relationship between fish catch and CIL, although the depth cut-off maybe somewhat deeper for ages 7 and 8. The depth range of 0–150 m continued to be definitive for the CIL water, although the largest part of the CIL was in the 50–100 m range (upper right panel of Fig. 9). Note that the proportion of CIL water on the bottom at 0–360 m in 4W was approximately half of that in 4Vs.

Temporal relationships

Associations between the abundance indices over time and variation in the proportion of cold intermediate layer water observed on the bottom during the surveys were tested by correlating the observed, log-

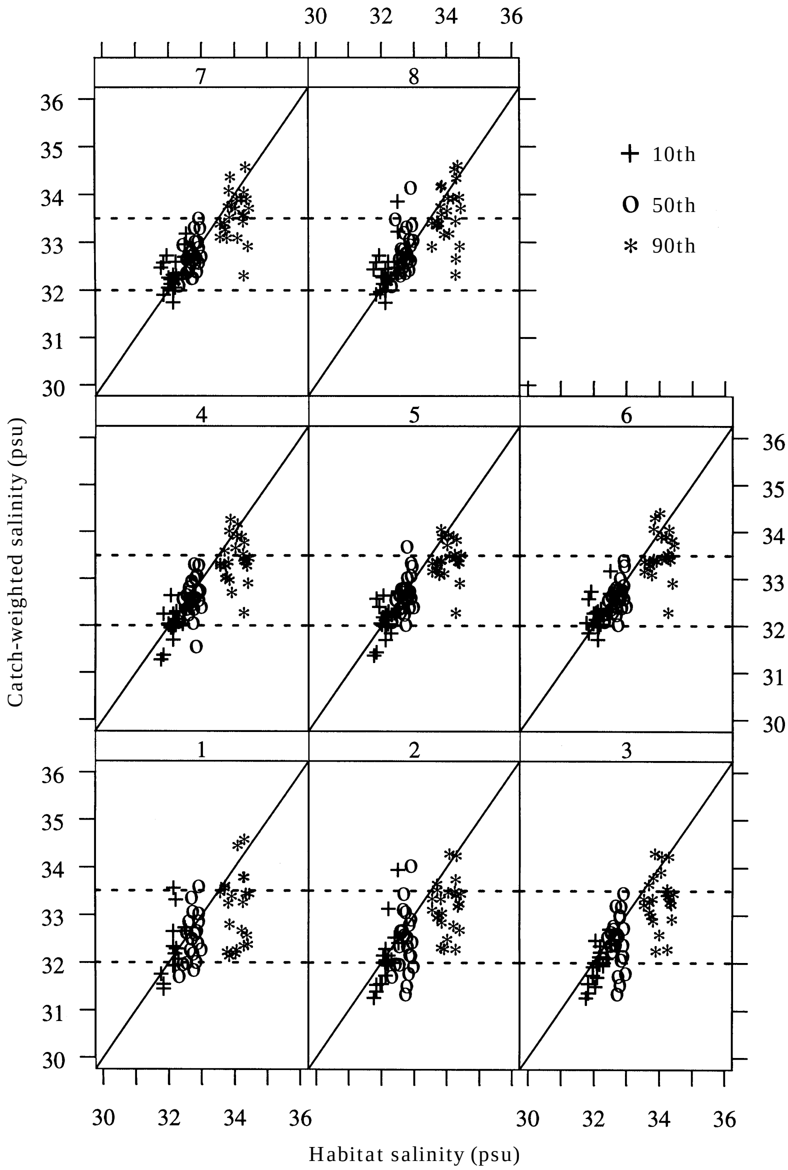


Figure 5. Trellis plot of the 10th, 50th, and 90th percentiles from the cumulative frequency curves for salinity (abscissa) and catch-weighted salinity (ordinate) for cod (*Gadus morhua*) in NAFO management area 4Vs by age group. Age one as indicated is in the lower left panel and age three in lower right. Age increases across the rows and up the columns of the panels. The dashed horizontal lines indicate the range of salinities which characterize the cold intermediate layer water mass. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

transformed, and rank-transformed stratified means by age with the time series for the proportion of cold intermediate layer for depths 0–150 m (Table 1). In 4Vs the correlations for all three forms of the stratified mean with the cold intermediate layer series were more significant for the older ages, in particular for ages 5 to 9. The rank correlation, which is robust to the larger stratified means, showed the strongest correlations (correlation coefficients = 0.44–0.52). We considered the significant correlation for age 1 to be dubious given that the cod of this age were rare in 4Vs with the maximum stratified mean of 0.95 cod per tow.

The correlation pattern was similar although weaker for the older ages in 4W. However, the correlations were much stronger for ages 2 and 3 in 4W (correlation coefficients = 0.45, 0.43, respectively) than in 4Vs.

We tested temporal associations further by modelling the stratified mean and proportion of bottom water characterized as CIL as a function of time using a locally weighted regression model (Cleveland and Devlin,

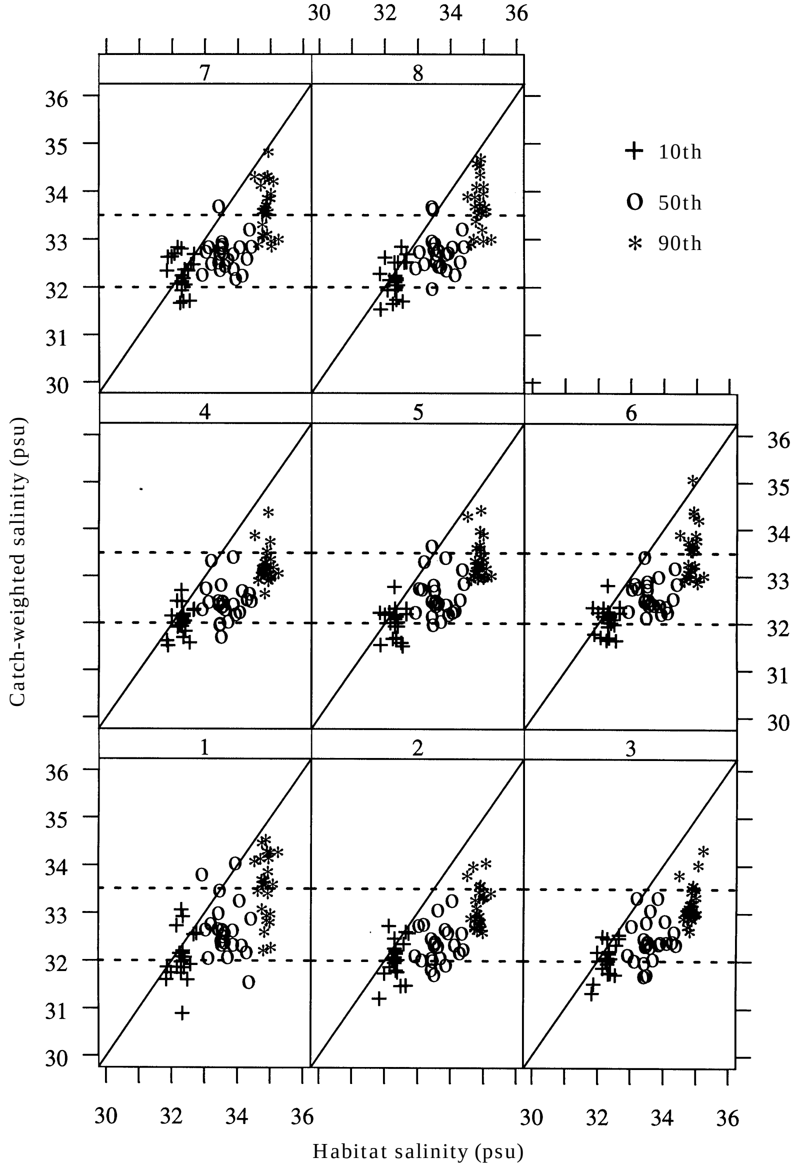


Figure 6. Trellis plot of the 10th, 50th, and 90th percentiles from the cumulative frequency curves for salinity (abscissa) and catch-weighted salinity (ordinate) for cod (*Gadus morhua*) in NAFO management area 4W by age group. Age one as indicated is in the lower left panel and age three in lower right. Age increases across the rows and up the columns of the panels. The dashed horizontal lines indicate the range of salinities which characterize the cold intermediate layer water mass. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

1988). This method is very useful for exploring data in that it uses a smoothing algorithm to relate the dependent variable to the independent variable and thus is more general than just using linear or polynomial functions. The dependent variable is smoothed as a function of the independent variable in a moving fashion over a local neighbourhood of observations analogous to computing a moving average. In our case, we arbitrarily chose the neighbourhood or span to contain 75% of the observations (i.e. observations over a 18 year span). Our aim was to look for patterns in the time series for stratified means and proportions of CIL in 4Vs and 4W at the same span.

The predicted values at each age for 4Vs and 4W were plotted as differences or anomalies from their respective mean predicted value in Fig. 10a and Fig. 11a, respectively. The *year-effects* were quite obvious and this time were not restricted to large catches only. That is, in 4Vs, most of the age classes follow a similar pattern during the mid-1970s when abundance appeared to be

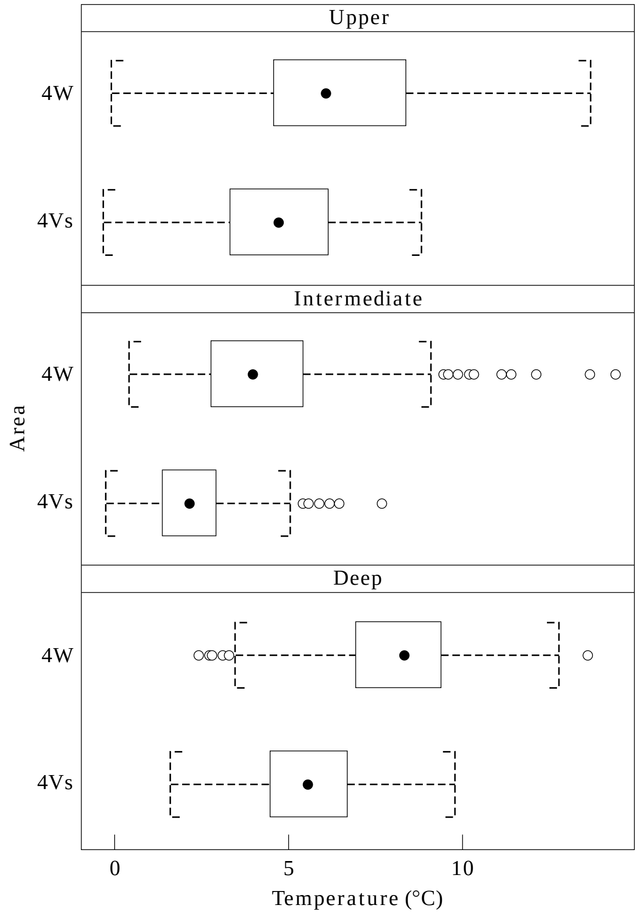


Figure 7. Boxplots of observed temperatures for specified salinity ranges from the July trawl surveys 1970–1993 for NAFO management areas 4Vs and 4W of the Eastern Scotian Shelf, Canada. Salinities are grouped by water mass type (Upper, Cold Intermediate, and Deep layers). Median represented as black circle within the box while the upper and lower boundaries of the box indicate the upper (75th) and lower (25th) quartiles, respectively. Horizontal lines from the boxes extend to 1.5 times the interquartile range or to the closest observed value. Open circles are used to indicate extreme values.

low as well as in the mid-1980s when large stratified means were observed. While the trend in 4W was somewhat similar for ages 1 to 4 during the early to mid-1970s, the increase started earlier than in 4Vs and decreased below the zero line for ages 1–3 by 1986–1987.

The lower panels in both figures present the observed and smoothed values from the locally weighted regression model of the estimated proportion of the bottom covered by the cold intermediate layer water mass. The temporal trend of the CIL also differs between the two areas, with the trend in 4Vs appearing to be coincident with that of the stratified means in the panel above. The observations for 1983 appears to be an outlier with respect to the overall trend relative to neighbouring values. Omitting this point from the analysis results in a much better fit of the locally-weighted regression with the R^2 increasing to 0.44 from 0.26. The R^2 is a relative measure only and can also be increased by decreasing the span.

A closer look at the trend in proportion of CIL over time showed that the 1983 observation was only out of line when the depth was restricted to be less than 150 m. In fact, 1983 was peculiar with respect to the depths of the sets in strata 44, the largest strata in 4Vs accounting for 0.36 of the area. The depth range for this strata was 92–183 m and, in 10 of the 24 years in the series, all of the sets were at depths less than 150 m, while in most of the remaining years, between 0.17 and 0.33 of the sets were deeper than 150 m. However, in 1977 and in 1983, the highest proportion (0.43 and 0.50, respectively) of sets occurred in depths deeper than 150 m. Coincidently, these were also the two lowest years for CIL at depths of 0–150 m in Figure 10b. Most sets in this strata exhibit salinities and temperatures consistent with the CIL over the 24 years but random sampling within strata may

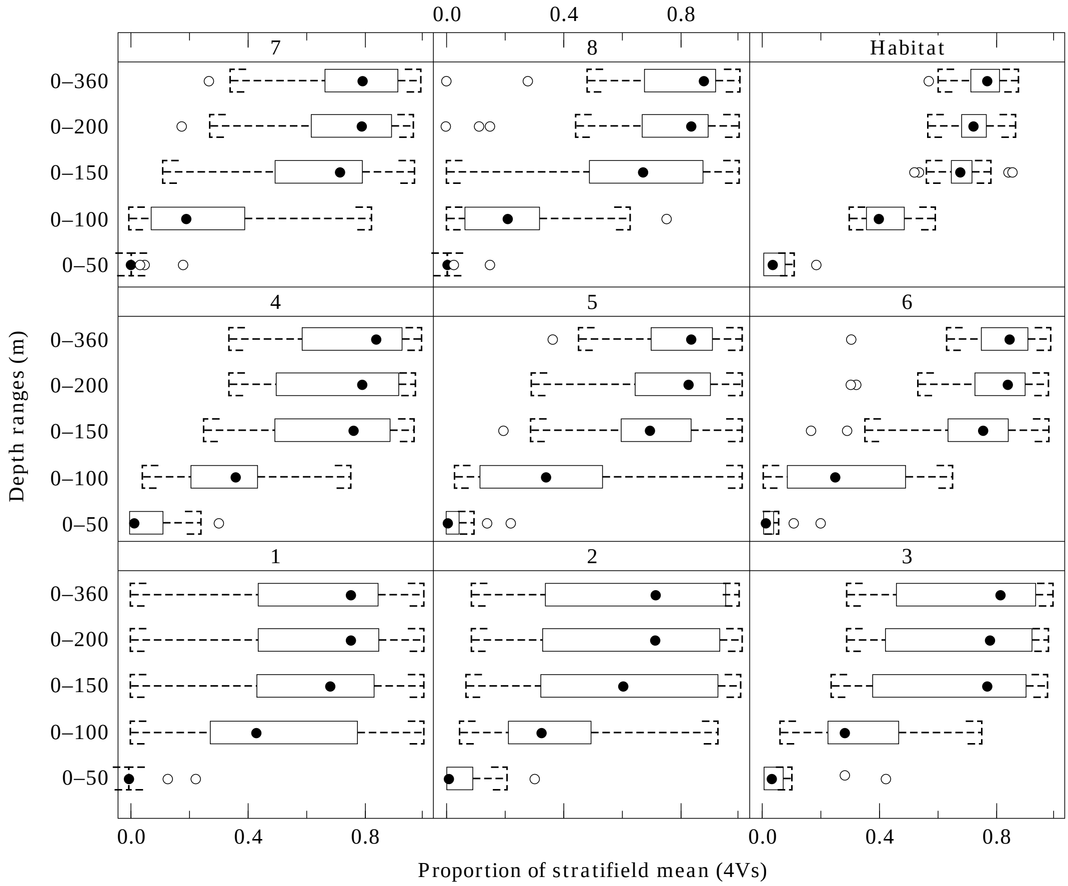


Figure 8. Boxplots of the proportion of the stratified mean abundance of cod (*Gadus morhua*) in each year (1970–1993) in NAFO management area 4Vs by age group, associated with the cold intermediate layer for different bottom depth ranges. Median represented as black circle within the box while the upper and lower boundaries of the box indicate the upper (75th) and lower (25th) quartiles, respectively. Horizontal lines from the boxes extend to 1.5 times the interquartile range or to the closest observed value. Open circles are used to indicate extreme values. Age one as indicated is in the lower left panel and age three in lower right. Age increases across the rows and up the columns of the panels. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

have resulted in estimates lower than the actual proportions of CIL in 1977 and 1983 for depths less than 150 m.

The trend of CIL in 4W appears to be opposite to that of the stratified means there. The 4W series exhibited a much weaker temporal signal at this span (0.75) than the 4Vs series with a relative R^2 of 0.08. The fact that the temperatures of the CIL are warmer in 4W than in 4Vs may suggest that the characteristics of this kind of water have changed as it has moved from 4Vs to 4W, resulting in a weakening of the temporal signal noted in Figure 10b. We will return to this point in the Discussion section.

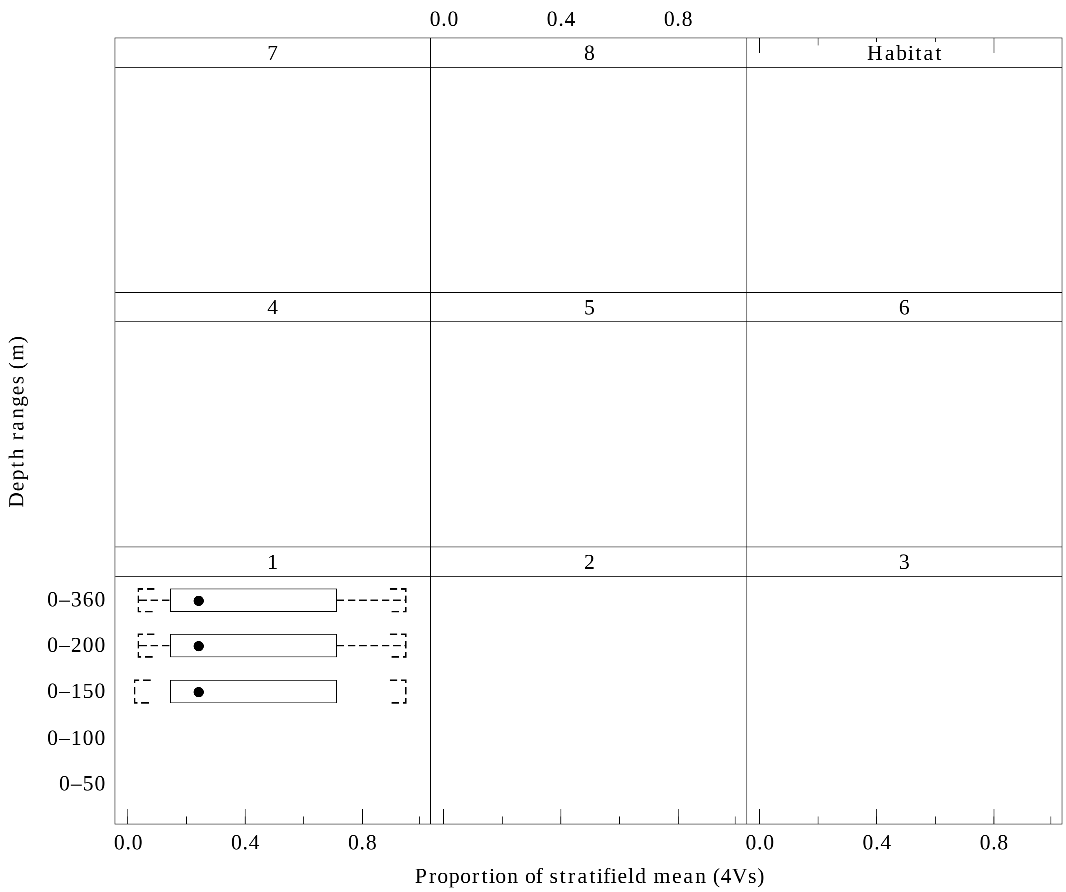
Temporal model of stratified means and CIL

The patterns in Figures 10 and 11 suggest that temporal trends in the stratified means and CIL may be related. We modelled the stratified means by age as either a function of the original CIL ($\mathbf{CIL_o}$) trend or a function of two terms, the smoothed CIL trend ($\mathbf{CIL_s}$) in the lower panels of Figures 10 and 11 and the residuals ($\mathbf{CIL_r}$) from these two trends. Exploratory plots of stratified means versus these covariates indicated that the variance was proportional to the mean. This suggests that we should model the distribution of the stratified mean as a Gamma random variate and use a log link to ensure that predicted values are greater than zero (McCullagh and Nelder, 1989). That is, for year k and age a we have either,

$$E(\bar{y}_{st,k,a}) = \exp\ \{\beta_0 + \beta_1\ (\mathbf{CIL_o})_k\},$$

or

$$E(\bar{y}_{st,k,a}) = \exp\ \{\beta_0 + \beta_1\ (\mathbf{CIL_s})_k + \beta_2\ (\mathbf{CIL_r})_k\},$$


7
8
Habitat
4
5
6
1
2
3
0–360
0–200
0–150
0–100
0–50
0.0
0.4
0.8
Depth ranges (m)
Proportion of stratifield mean (4Vs)

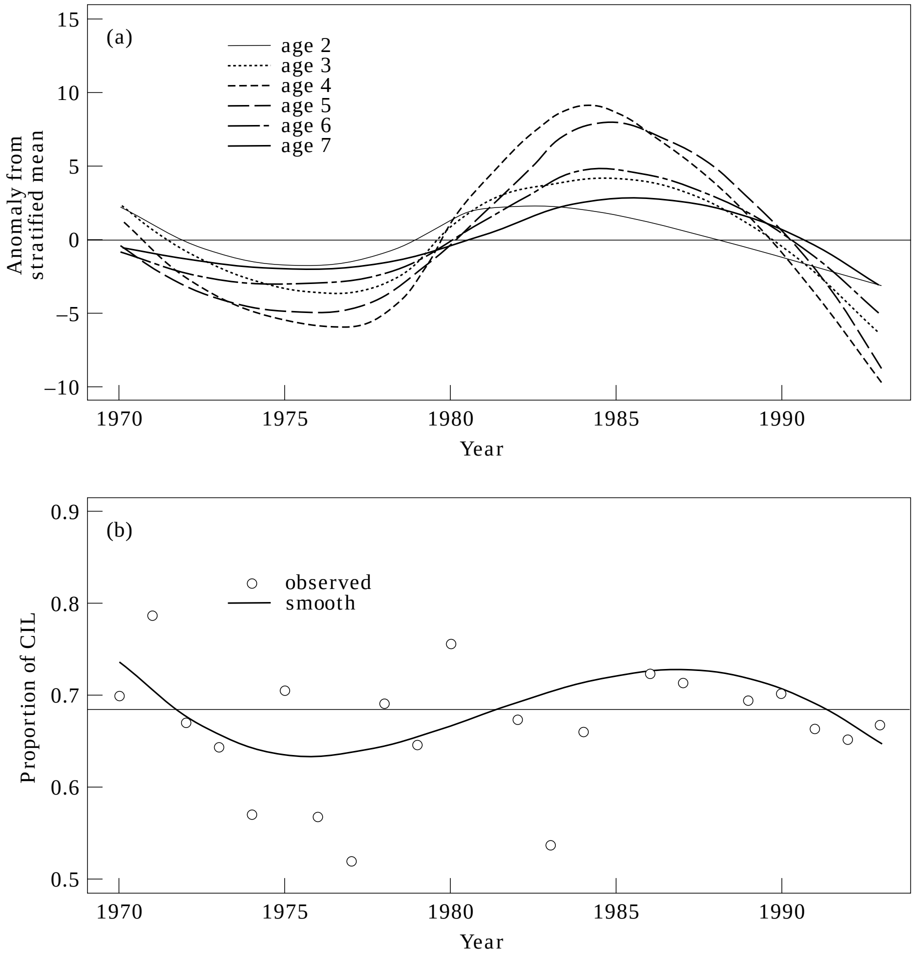


Figure 10. Smoothed curves from locally-weighted regression models fitted to (a) stratified mean number of cod by age and (b) cold intermediate layer water mass in NAFO management area 4Vs as a function of time. All smoothed values for the cod have been centered by their respective means at age. Age 1 and 8 curves not shown because they were coincident with zero line for the scale used in this plot. The horizontal line on lower panel indicates the mean smoothed value for cold intermediate layer water mass. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

where the β_i's (i=0, 1, 2, 3) are parameters to be estimated. The models were fitted to the data using iteratively reweighted least squares and terms were tested by being added sequentially. The significance of the $\mathbf{CIL_o}$, $\mathbf{CIL_s}$, and $\mathbf{CIL_r}$ terms was determined by using the analysis of deviance approached given in McCullagh and Nelder (1989). Visual inspection of the deviance residual plots (not included here) for all significant models in 4Vs and 4W indicated that the Gamma model was adequate for these data.

The Gamma models provided similar results to those in Table 1 with respect to older ages (5 and older) showing stronger relationships with the $\mathbf{CIL_o}$ in 4Vs than the younger age groups (Table 2). Removal of the 1983 observations from the analysis resulted in more significant relationships for ages 6 to 8 with age 5 being marginal. Relationships were particularly strong for the smoothed trend ($\mathbf{CIL_s}$) from the locally-weighted regression model for the CIL and the stratified mean in 4Vs. This result is not too surprising given the coincidental temporal patterns captured by the fitted smoothed curves in both panels of Figure 10. The similarity of these results to those from fitting the stratified means to the observed CIL data excluding the 1983 point are not unexpected given that the 1983 point was excluded because it appeared to be an outlier from the smooth curve. However, both results suggest that the trend in the stratified mean in 4Vs is strongly related to an underlying temporal signal in the CIL that appears to be characterized by the smooth curve in Figure 10.

The pattern in 4W showed the younger ages (ages 1–3) had a strong relationship with the observed $\mathbf{CIL_o}$ only while the older ages did not show relationships with any

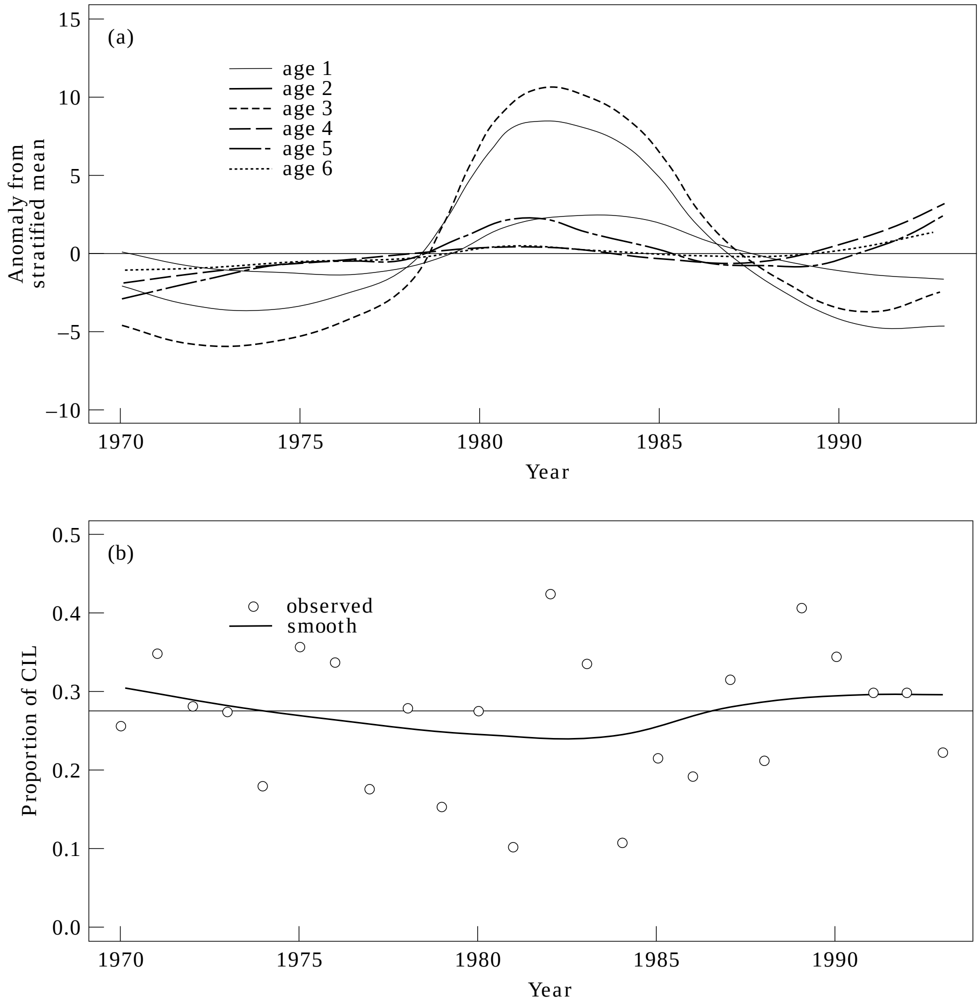


Figure 11. Smoothed curves from local regression models fitted to (a) stratified mean number of cod by age and (b) proportion of cold intermediate layer water mass in NAFO management area 4W as a function of time. All smoothed values for the cod have been centered by their respective means at age. Age 7 and 8 curves not shown because they were coincident with zero line for the scale used in this plot. The horizontal line on lower panel indicates the mean smoothed value for cold intermediate layer water mass. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

function of the CIL. There was no evidence for strong temporal patterns in Figure 11b and hence showed no significant relationships between $\mathbf{CIL_s}$ and the stratified mean. Again, we suggest that warming of the CIL water as it moves from 4Vs to 4W may have resulted in weakening of the temporal pattern noted for the 4Vs data.

If these models characterize the CIL component in the temporal trend of the stratified means, then removal of this CIL trend could result in a series that provides a better representation of the temporal trends in true population abundance. While this latter supposition may not be readily verifiable, we can test to see if abundance indices based on corrections for the CIL offer a more consistent measure of year-class strength. That is, the Friedman rank sum test can be used as before to test for consistent ranking of cohorts between age groups in the corrected series. We tested this null hypothesis for 4Vs and 4W using only those ages for which significant relationships were found in Table 2; ages 4 to 8 (1966 to 1985 cohorts) and $\mathbf{CIL_s}$ in 4Vs and ages 1 to 3 (1969–1990 cohorts) and $\mathbf{CIL_o}$ in 4W. Corrected series for the CIL were made by subtracting the predicted series for the Gamma models from the original stratified means series. In both cases we could not reject the null hypothesis for the corrected series (p-values = 0.154 for 4Vs and 0.872 for 4W). When we tested the original stratified means for these same ages and cohorts, the null hypothesis was rejected for both areas (p-value < 0.001).

Table 2. Results of analysis of deviance for individual terms of model, stratified mean = exp($\beta_0 + \beta_1\{\mathbf{CIL_o}\}$) or stratified mean = exp($\beta_0 + \beta_1\{\mathbf{CIL_s}\} + \beta_2\{\mathbf{CIL_r}\}$) with a Gamma distributed error. $\mathbf{CIL_s}$ and $\mathbf{CIL_r}$ refer, respectively, to the smoothed and residual values of a locally-weighted regression model of the observed proportion of cold intermediate layer water mass ($\mathbf{CIL_o}$, 0–150 m) as a function of time. Entries are p-values for χ^2 statistic. Bracketed entries in the $\mathbf{CIL_o}$ column for 4Vs refer to the fit when data for 1983 were excluded. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada.

Age (yr)	4Vs			4W		
	$\mathbf{CIL_o}$	$\mathbf{CIL_s}$	$\mathbf{CIL_r}$	$\mathbf{CIL_o}$	$\mathbf{CIL_s}$	$\mathbf{CIL_r}$
1	0.071 (0.249)	0.773	0.041	0.023	0.197	0.589
2	0.989 (0.681)	0.155	0.405	<0.001	0.263	0.863
3	0.505 (0.421)	0.096	0.932	0.004	0.435	0.737
4	0.473 (0.285)	0.010	0.849	0.282	0.090	0.117
5	0.189 (0.072)	0.001	0.855	0.725	0.111	0.422
6	0.099 (0.010)	<0.001	0.549	0.075	0.079	0.480
7	0.026 (0.012)	<0.010	0.506	0.143	0.209	0.594
8	0.051 (0.016)	<0.001	0.366	0.193	0.601	0.583

The corrected, predicted and observed series are presented for age 5 in 4Vs and age 2 in 4W in Figures 12a and b, respectively, to illustrate the effect of correcting the stratified mean for the trends in CIL. In 4Vs, the major effects were to decrease the survey index in those years when the CIL was becoming increasingly widespread (e.g. 1980–1987) relative to those years in which the CIL was less available and stable (1974–1979). In particular, note that 5 year-olds in 1986 were originally observed to be more abundant than 5 year-olds in the mid-1970s whereas the corrected series suggests that this age group in 1986 was less abundant than those in the earlier time period. The effect is similar in 4W but less dramatic given the lack of temporal trend in the CIL there.

Discussion

Our findings that there was age segregation of cod in 4VsW, with 4W being predominantly a young fish area and that there were age-specific associations between bottom trawl catches of 4VsW cod and water temperature, salinity, and depth, are not new. However, they agree with the findings of Jean (1964) and confirm the analyses of Sinclair (1992) and Page *et al.* (1994). Jean (1964) reported that during a summer survey conducted in 1960 in the 4VsW area the largest catches of cod occurred at depths less than 150 m and near-bottom temperatures below 6°C. Unfortunately, Jean did not report the salinity ranges for these catches. Sinclair (1992) analyzed the 1970–1989 subset of the present data and showed that in the 4VsW area the cod tended to associate with cooler temperatures as they got older and that this shift in association coincided with a shift in distribution from 4W to 4Vs and from relatively shallow to deeper waters. Page *et al.* (1994) conducted a preliminary analysis of the age-specific associations between cod and water temperature, salinity, and depth for the entire Canadian Scotian Shelf/Georges Bank groundfish bottom-trawl dataset. They also showed a general tendency for older cod to be found in deeper water in many of the NAFO areas 4VWX. Similar results were reported by Swain (1993) for age and depth relationships for cod in NAFO area 4T (Southern Gulf of St Lawrence) and by Macpherson and Duarte (1992) for demersal fish in general.

The refinements that we introduced here are that the annual estimates of the stratified mean abundance of cod are dominated by sets that occur primarily within the depth range of 50–150 m, and in the salinity and temperature ranges that are used to identify the CIL. Further, we showed that some of the inter-annual variation in the cod abundance estimates was associated with variability in the proportion of the bottom covered by the CIL. When this association is taken into account, the inconsistencies, or year-effects, in the cod abundance time series are reduced below the limits of statistical detection. Smith *et al.* (1991) showed that a relationship existed between the estimated abundance of age 4 cod during the 1979–1988 spring surveys in 4VsW and the proportion of the bottom covered by CIL type water. This association with the CIL is also consistent with the results of Sinclair (1992) with respect to the range of temperatures that he studied.

The CIL flows into the eastern Scotian Shelf area from the Gulf of St Lawrence and initially into the 4Vs area. As the water continues to move into the 4W area, it gains heat from the warmer upper and lower layers surrounding it and its temperature increases, helping to make the 4W temperatures higher (Houghton *et al.*, 1978). The waters within 4W were also warmer and more saline than those in 4Vs because of the greater influence of the relatively warm and more saline offshore waters which periodically move into the 4W area. These processes contribute to the fact that the temporal trend in the CIL was much stronger in 4Vs than in 4W.

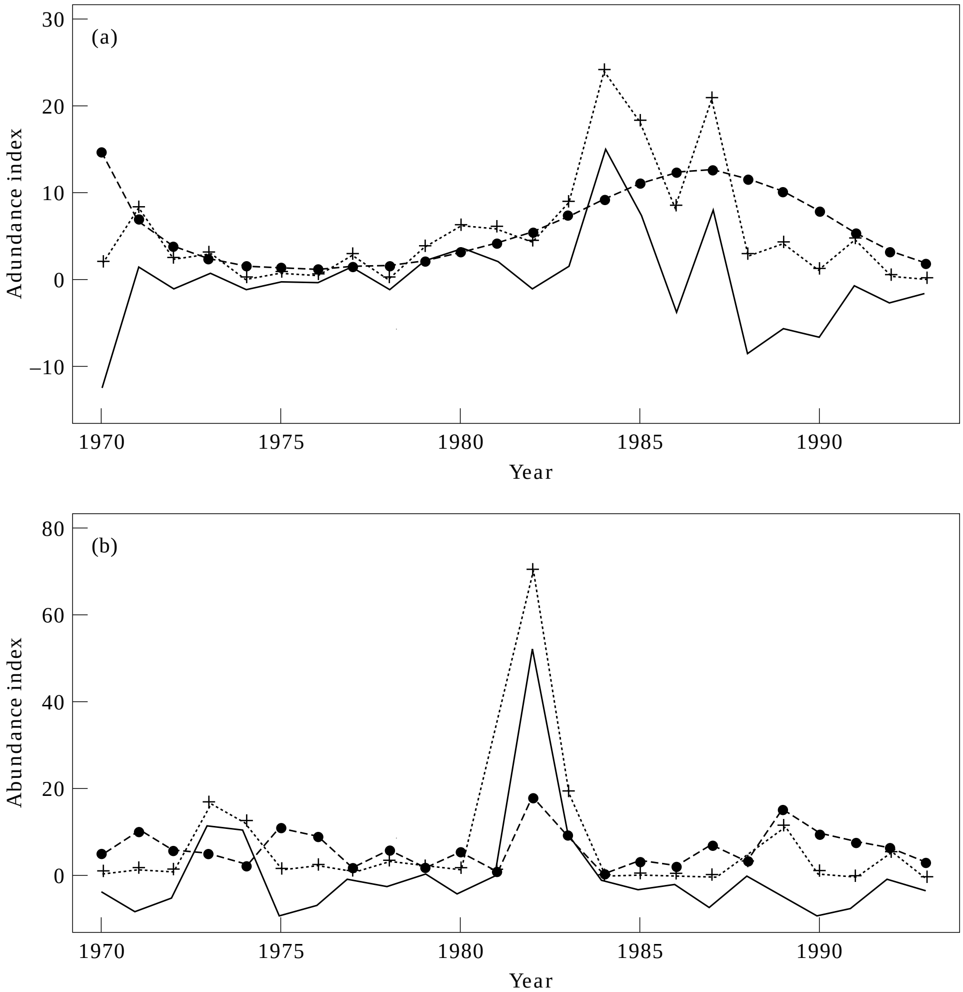


Figure 12. Comparison of trends in stratified mean abundance of cod with those predicted by the CIL models developed in the text and the corrected series from the CIL model for (a) age 5 in 4Vs and (b) age 2 in 4W. The data are from the July trawl surveys of the Eastern Scotian Shelf, Canada. (——) Corrected series; (– – –) predicted series; (· · · ·) observed series.

The ages for which significant relationships were found in the Gamma models corresponded to those age groups that were generally more abundant in each area, i.e. ages 1 to 3 in 4W and 4 to 8 in 4Vs (see Fig. 4). This pattern may reflect the fact that the CIL made up a larger portion of the deeper bottom water in 4Vs than in 4W (Figs 8, 9) due to the processes discussed above. Given the evidence for age-specific temperature associations (e.g. Sinclair, 1992), the fact that the CIL water was warmer in 4W than it was in 4Vs may also underlie this age/area pattern.

While it is the combinations of temperature and salinity that are used to define water masses, temperature has usually been identified as the more important factor (e.g. Jean, 1964; Sinclair, 1992; Swain and Kramer, 1995) in determining the distribution of cod. Lambert *et al.* (1994) investigated the effects of three salinity levels (7, 14, and 28 psu) on the growth rate and food conversion of cod. Their results indicated that higher growth rates and better food conversion rates were obtained at the lower salinity levels (7 and 14 psu) than at 28 psu. These results may suggest that salinities of 32–33.5 psu were more favourable for the cod than higher salinities. However, the fact that the cod did not associate solely with available salinities less than 32 psu also suggests that there was something else about the CIL water with which the cod strongly associated. Lacking measurements on any other characteristic of the water we can only offer temperature as the something else and suggest that salinity appears important only in its identification of a cold water mass within a particular depth range from a particular source.

The association of large cod catches with certain environmental conditions has often been interpreted, perhaps loosely, as evidence that such environmental conditions are preferred by cod (e.g. Jean, 1964; Scott, 1982; Smith *et al.*, 1991; Sinclair, 1992; Swain and Kramer, 1995). In this context, the ontogenetic movement of cod from 4W to 4Vs is a consequence of their search for preferred conditions. When the area over which the CIL impinges on the bottom is relatively large, the cod are closer to and more widespread on the bottom. Therefore, the cod will be more available to the bottom trawl and, consequently, catches will be relatively high. On the other hand, when little CIL impinges on the bottom, the cod will be higher up in the water column and unavailable to the bottom trawl resulting in low survey catches. Such a mechanism may explain Godø and Wespestad's (1993) observation of annual variability in the differential availability of cod to bottom trawl and acoustic gear in the north-east Arctic cod stock. Years where abundances of cod appeared high (low) in the bottom trawl, acoustically determined cod abundances were low (high).

The preference point of view suggests that the relationship between CIL and cod catches will be positive, as in 4Vs. In 4W, the relationship was not so clear because the CIL temperatures were higher than in 4Vs, indicating a change in the characteristics of this water mass. The temperature contrast between the near-bottom and mid-depth in 4W was presumably less and the preference behaviour there would therefore not be as strong. The catches of older cod would be less in 4W than in 4Vs because there was less of the preferred water available on the bottom. The association of older cod with deeper depths may simply be an artifact of the fact that the 4Vs area is deeper than in 4W.

The preference point of view is not exclusive. The associations may also be reflections of availability and catchability. Studies of the swimming speeds of cod at low temperatures (Beamish, 1966; He, 1991) indicate that cod have a much reduced swimming endurance in these conditions. More specifically, He (1991) reported that cod, 36–46 cm in length, could only maintain a speed of 1 m s^{-1} for 2 min at temperatures of approximately 0.8°C. Beamish (1966) reported that cod 36 cm in length could only maintain 0.9 m s^{-1} for 12 min at 5°C. During the surveys analyzed here, the large catches of cod occurred at temperatures less than 5°C and often close to 1°C, and the survey vessels aimed to maintain a towing speed of 3.5 knots or 1.77 m s^{-1} for 30 min. Figure 15 of Strong (1992) indicates that the speed of the trawl over bottom may be between 1.2 and 2.2 m s^{-1} at this towing speed.

Therefore it is possible that large catches may be due to the cod's inability to out-swim the trawl at temperatures <5°C rather than the presence of large numbers of fish congregating in preferred conditions. Furthermore, the observed age segregation between 4Vs and 4W may simply be a function of the 4Vs area being generally deeper than 4W and that cod, like other demersal fish (Macpherson and Duarte, 1992), tend to move to deeper water with age. The temperature of the water in 4Vs was less than 5°C and colder than in 4W. The cod are therefore less able to out-swim the bottom trawl in 4Vs than in 4W, resulting in the survey finding more cod in the deeper waters of 4Vs than 4W. Swain and Kramer's (1995) investigations of the associations between cod and temperature in the southern Gulf of St Lawrence indicated that cod tended to select colder temperatures at higher levels of abundance for metabolic reasons. However, since the determination of the levels of abundance were based on the estimates from the survey, our swimming speed explanation would suggest that the cod were more catchable when the temperatures were colder and, hence, it only appeared that abundance was higher. Alternatively, cod may select colder temperatures at higher levels of abundance, but the swimming speed/temperature relationship would imply that the survey estimates of these levels of abundance would be exaggerated.

We have proposed that the combination of salinity and temperature which defines the cold intermediate layer water mass is important with respect to trends in the abundance indices of cod in the 4VsW area. This may be too simplistic since it ignores other factors such as dissolved oxygen (D'Amours, 1993), although the latter may be correlated with the temperature and salinity signal. Whether the large catches or year-effects in the surveys are due to increased cod availability because of towing in preferred water or increased ease of capture due to low temperatures, survey trends need to be interpreted in conjunction with trends in the relevant environmental variables. Similarly, trends in indices of commercial catch per unit effort, especially for trawlers, should also be interpreted cautiously. Finally, fluctuations in estimated stock abundance generated by stock assessment procedures that do not consider such influences could potentially be misinterpreted as fluctuations in real stock abundance.

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